Vision

The vision for the road map is to possess the scientific understanding of carbon sequestration and develop to the point of deployment those options that ensure environmentally acceptable sequestration to reduce anthropogenic CO_2 emissions and/or atmospheric concentrations. The goal is to have the potential to sequester a significant fraction of 1 GtC/year in 2025 and of 4 GtC/year in 2050.

1 CARBON SEQUESTRATION: A THIRD APPROACH TO CARBON MANAGEMENT

1.1 CARBON MANAGEMENT

1.1.1 The Challenge

In the past 60 years, the amount of anthropogenic carbon dioxide (CO_2) emitted to the atmosphere, primarily because of expanding use of fossil fuels for energy, has risen from preindustrial levels of 280 parts per million (ppm) to present levels of over 365 ppm (Keeling and Whorf 1998).

Predictions of global energy use in the next century suggest a continued increase in carbon emissions and rising concentrations of CO_2 in the atmosphere unless major changes are made in the way we produce and use energy—in particular, how we manage carbon. For example, the widely cited IS92a ("business as usual") energy scenario developed by the Intergovernmental Panel on Climate Change (IPCC 1996) predicts that future global emissions of CO_2 to the atmosphere will increase from 7.4 billion tonnes of atmospheric carbon (GtC) per year in 1997 to approximately 26 GtC/year by 2100. Although the effects of increased CO_2 levels on global climate are uncertain, there is scientific consensus that a doubling of atmospheric CO_2 concentrations could have a variety of serious environmental consequences in the next century.

What would it take to stabilize the atmospheric concentrations of CO_2? Two widely used scenarios, a "business as usual" and an atmospheric stabilization scenario, are compared in Fig. 1.1. The difference between the two scenarios, about 1 GtC per year in 2025 and about 4 GtC per year in 2050, represents one estimate of the CO_2 reductions required to reach atmospheric stabilization. This road map identifies a framework for research and development (R&D) that would

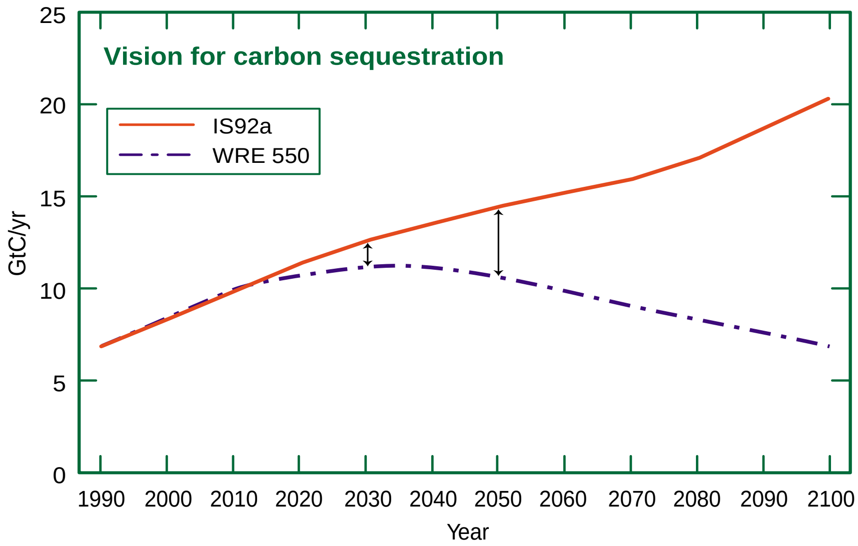

Fig. 1.1. One representation of the reductions in CO_2 that would be necessary to reach atmospheric stabilization compares the IS92A (business as usual) scenario with a scenario (WRE550) that leads to stabilized atmospheric CO_2 concentrations of 550 ppm (about twice preindustrial levels). The WRE550 scenario is commonly used by analysts of climate change. *Source:* Wigley, Richels, and Edmonds 1996.

allow carbon sequestration to provide a significant fraction of that reduction.

1.1.2 The Vision

The vision for the road map is to possess the scientific understanding of carbon sequestration and develop to the point of deployment those options that ensure environmentally acceptable sequestration to reduce anthropogenic CO_2 emissions and/or atmospheric concentrations. The goal is to have the potential to sequester a significant fraction of 1 GtC/year in 2025 and of 4 GtC/year in 2050.

1.1.3 Three Approaches to Carbon Management

Carbon sequestration is distinguished from, but complements, two other approaches to carbon management that are supported by the U.S. Department of Energy (DOE) (National Laboratory Directors 1997).

The first approach is to increase the efficiency of primary energy conversion and end use so that fewer units of primary fossil energy are required to provide the same energy service. DOE is sponsoring a variety of R&D programs to develop more efficient supply- and demand-side technologies (e.g., more efficient fossil-fuel-fired power plants, buildings, appliances, and transportation vehicles) and to find ways to produce and deliver electricity and fuels more efficiently. More efficient energy conversion and end use will result in lower CO_2 emissions per unit of energy service.

A second approach is to substitute lower-carbon or carbon-free energy sources for our current sources. For example, this strategy might involve substituting lower-carbon fossil fuels such as natural gas for coal or oil; using renewable energy supplies such as solar, wind, or biomass; or increasing the use of nuclear power. DOE has major R&D programs to develop more efficient fossil energy as well as renewable energy and nuclear energy technologies.

Carbon sequestration could represent a third approach in addition to efficiency improvements and evolution toward low-carbon fuels. However, it has received much less attention to date than these other two approaches.

1.1.4 What is Carbon Sequestration?

Carbon sequestration can be defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere. The idea is (1) to keep carbon emissions produced by human activities from reaching the atmosphere by capturing and diverting them to secure storage, or (2) to remove carbon from the atmosphere by various means and store it.

One set of options involves capturing carbon from fossil fuel use before it reaches the atmosphere. For example, CO_2 could be separated from power plant flue gases, from effluents of industrial processes (e.g., in oil refineries and iron, steel, and cement production plants), or during production of decarbonized fuels (such as hydrogen produced from hydrocarbons such as natural gas or coal). The captured CO_2 could be concentrated into a liquid or gas stream that could be transported and injected into the ocean or deep underground geological formations such as oil and gas reservoirs, deep saline reservoirs, and deep coal seams and beds. Biological and chemical processes may convert captured CO_2 directly into stable products. Atmospheric carbon can also be

Why is Carbon Sequestration Important?

It is important to carry out research on carbon sequestration for several reasons:

- Carbon sequestration could be a major tool for reducing carbon emissions from fossil fuels. However, much work remains to be done to understand the science and engineering aspects and potential of carbon sequestration options.
- Given the magnitude of carbon emission reductions needed to stabilize the atmospheric CO_2 concentration, multiple approaches to carbon management will be needed. Carbon sequestration should be researched in parallel with increased energy efficiency and decarbonization of fuel. (These efforts should be closely coordinated to exploit potential synergies.)
- Carbon sequestration is compatible with the continued large-scale use of fossil fuels, as well as greatly reduced emissions of CO_2 to the atmosphere. Current estimates of fossil fuel resources—including conventional oil and gas, coal, and unconventional fossil fuels such as heavy oil and tar sands—imply sufficient resources to supply a very large fraction of the world's energy sources through the next century.
- The natural carbon cycle is balanced over the long term but dynamic over the short term; historically, acceleration of natural processes that emit CO_2 is eventually balanced by an acceleration of processes that sequester carbon, and vice versa. The current increase in atmospheric carbon is the result of anthropogenic mining and burning of fossil carbon, resulting in carbon emissions into the atmosphere that are unopposed by anthropogenic sequestration. Developing new sequestration techniques and accelerating existing techniques would help diminish the net positive atmospheric carbon flux.

captured and sequestered by enhancing the ability of terrestrial or ocean ecosystems to absorb it naturally and store it in a stable form.

1.1.5 Necessary Characteristics for Carbon Sequestration Systems

Any viable system for sequestering carbon must have the following characteristics.

Capacity and price. The technologies and practices to sequester carbon should be effective and cost-competitive. This road map will focus on options that allow sequestration of a significant fraction of the goal.

Environmentally benign fate. The sheer scale and novelty of sequestration suggests a careful look at environmental side effects. For example, the long-term effects of sequestration on the soil or vegetation need to be understood. Until recently, dilution into the atmosphere was considered acceptable. Vast quantities of materials would be generated. The safety of the product and the storage scheme have to be addressed.

Stability. The carbon should reside in storage for a relatively long duration.

1.2 THE GLOBAL AND THE FOSSIL FUEL CARBON CYCLES

Carbon sequestration is intimately tied to two carbon cycles— the natural and the fossil fuel cycles. Understanding aspects of both cycles provides a context for developing carbon sequestration options.

1.2.1 The Global Carbon Cycle

Improving our understanding of the global carbon cycle, its fluxes, and its reservoirs, is intimately tied to successful implementation of carbon sequestration technologies. Decreasing atmospheric CO_2 concentrations by reducing CO_2 emissions or by changing the magnitude of the fluxes between reservoirs is controlled by the carbon budget of a reservoir. From a carbon sequestration perspective, understanding the potential to alter carbon budgets through the intervention of carbon sequestration technologies to reduce future atmospheric CO_2 concentrations is one of the principal challenges.

Human activities during the first half of the 1990s have contributed to an average annual emission of approximately 7.4 GtC into the atmosphere (Fig. 1.2). Most of these emissions were from fossil fuel combustion. The net result of these CO_2 emissions during the first part of the 1990s was an annual net emissions increment to the atmosphere of 3.5 GtC. Storage of carbon in terrestrial systems due to photosynthesis and plant growth was 1.7 GtC. Another 2.2 GtC per year was taken up by oceans.

Carbon fluxes between the atmosphere and ocean/terrestrial reservoirs are quite large (hundreds of GtC per year), while net carbon exchange is over an order of magnitude smaller. For example, the average net ecosystem accumulation of the terrestrial biosphere was 0.3 GtC per year (1.7 GtC per year net ecosystem production diminished by 1.4 GtC per year due to land clearing), while terrestrial

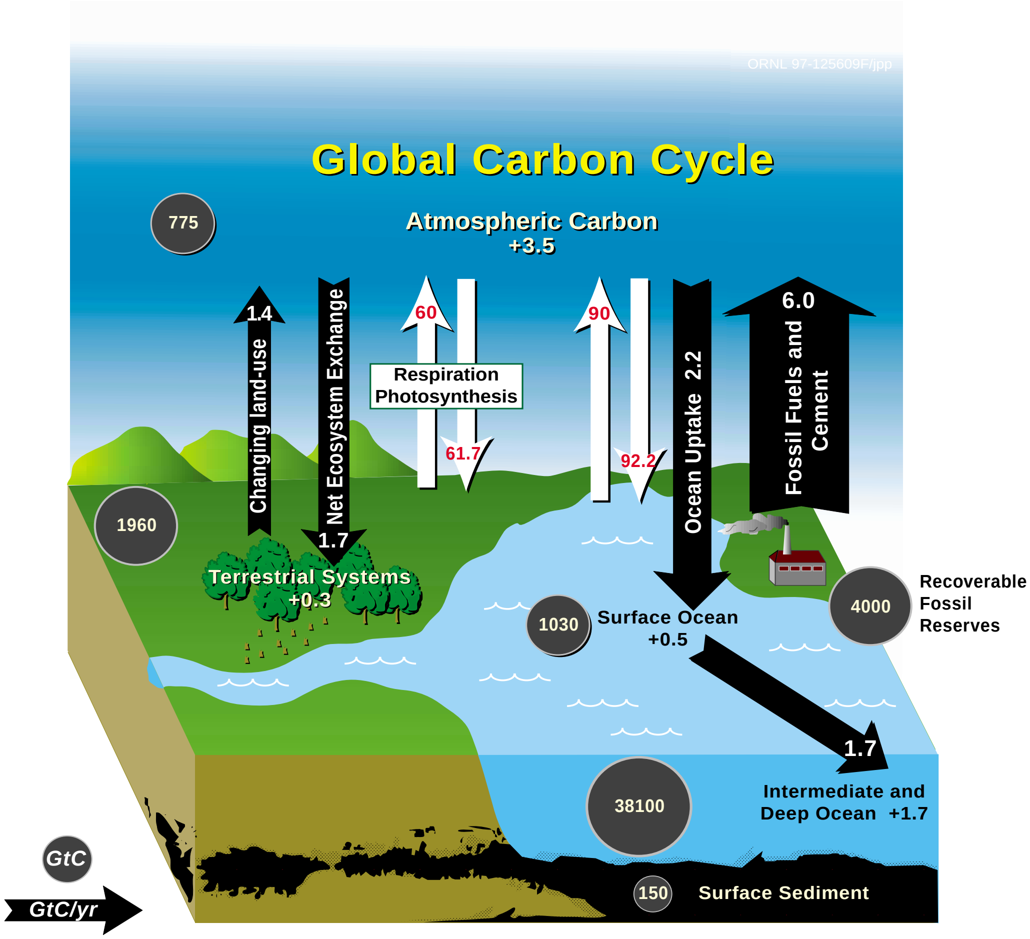

Fig. 1.2. Human-induced changes in the global carbon cycle resulting from increases in the combustion of fossil fuels and changing land-use patterns. Solid arrows indicate the average magnitude of perturbation in carbon fluxes and the fate of carbon resulting from these activities averaged for the first half of the 1990s. Net fluxes (black arrows) and gross fluxes (gray arrows) are in billions of tonnes of carbon per year. Annual net additions of carbon (shown as + numbers) to the atmosphere, ocean subsystems, and terrestrial systems from anthropogenic sources are in billions of tonnes of carbon per year. Pool sizes (circles) are shown in billions of tonnes of carbon. For more information, see Houghton 1995 and Marland et al. 1998. *Source: Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions*, modified from IPCC 1996.

ecosystems photosynthetically fixed 61.7 GtC per year—the photosynthesis uptake being offset by 60 GtC per year due to plant/soil respiration. Similarly, the net ocean uptake of 2.2 GtC per year is the difference of ocean/atmosphere fluxes each exceeding 90 GtC per year. The significance of understanding these complicated carbon exchanges is that developing the ability to alter these gross annual carbon exchanges of the global carbon cycle by a small percentage through carbon sequestration technologies would increase net storage of carbon in the major reservoirs and lessen atmospheric carbon concentrations.

1.2.2 The Fossil Fuel Cycle

About 75% of the world's commercial energy comes from fossil fuels, and about 84% of the energy used in the United States is derived from fossil fuels (EIA 1998a; PCAST 1997). Given the advantages inherent in fossil fuels, such as their cost-competitiveness, their availability, their ease of transport and storage, and the large fossil resources, fossil fuels are likely to remain a major player in global energy supply for at least the next century.

Figure 1.3 shows the energy flows through the U.S. economy from fossil and other fuels. This diagram helps to identify places where CO_2 could be separated and captured, but there are energy and cost implications that must be considered (Hoffert et al. 1998). In the near term, most of the CO_2 captured is likely to come from electricity generated from fossil fuels, because large quantities of it could be processed at fixed locations. However, other possibilities become more likely in the longer term. Fossil fuels, solid waste, or biomass can be "decarbonized" so that a higher-energy-content and environmentally benign fuel is separated from CO_2. For example, either a fossil energy source or another carbon source such as solid waste or biomass could be pretreated to produce hydrogen and CO_2. These central pretreatment facilities could become other new sources of carbon for capture.

1.3 APPROACH AND SCOPE OF THIS REPORT

The goal of this report is to identify key areas for R&D that could lead to a better understanding of the potential use of carbon sequestration as a major tool for managing carbon emissions. Under the leadership of DOE, researchers from universities, industry, other government agencies, and DOE national laboratories were brought together to develop the technical basis for developing an R&D road map. This report develops much of the information needed for the road map.

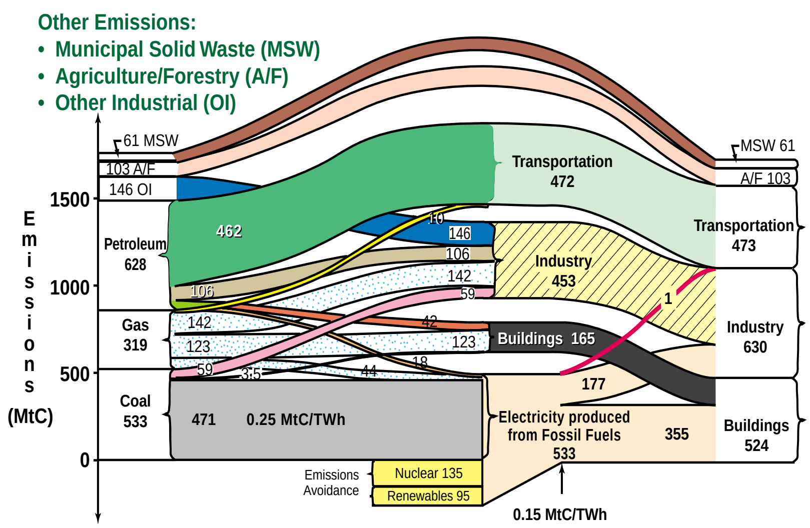

Fig. 1.3. Carbon flows in the energy system and sources of emissions in the United States in 1995 (in millions of metric tons equivalent). Electricity produced by the combustion of fossil fuels is likely to remain a significant contributor to greenhouse gas emissions. *Sources:* EIA 1998a,b.

Six scientific/technical "focus areas" relevant to carbon sequestration were identified, and groups of experts in each area reported on the R&D issues. These focus areas are

1. Separation and Capture of CO_2
2. Ocean Sequestration
3. Carbon Sequestration in Terrestrial Ecosystems (Soils and Vegetation)
4. Sequestration of CO_2 in Geological Formations
5. Advanced Biological Processes for Sequestration
6. Advanced Chemical Approaches to Sequestration

These six focus areas represent one way to organize the scientific and engineering issues underlying carbon sequestration.

Our vision for a carbon sequestration road map is to conduct the appropriate R&D so that options will be available for significantly reducing anthropogenic carbon emissions in the time frame of 2025 and beyond.

This report describes the R&D necessary to understand and develop to the point of deployment all critical options bearing on the capture, transport, conversion, and sequestration of carbon (Fig. 1.4). It addresses known sources of carbon (industrial sources, power plant flue gases, carbon split away from fossil fuels before combustion); carbon forms for sequestration (CO_2, elemental carbon, and minerals that contain carbon); and options for sequestration sinks (oceans, geologic formations, enhancing the natural carbon cycle).

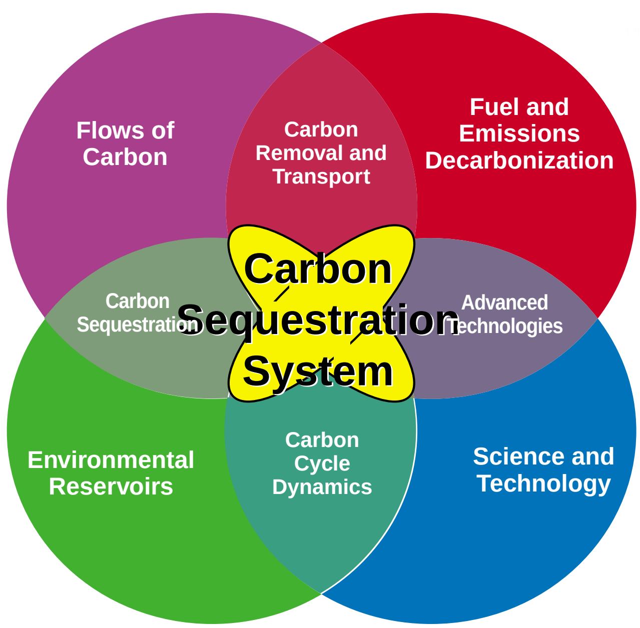

Fig. 1.4. Deploying an effective carbon sequestration system will require an integrated program of science, enabling technology, and advanced power systems—all dependent on better understanding of environmental carbon dynamics.

1.4 TOWARD DEVELOPMENT OF A CARBON SEQUESTRATION ROAD MAP

An emerging technology road map provides—and encourages the use of—a structured R&D planning process. Emerging technology road maps furnish a framework for managing and reviewing the complex, dynamic R&D process needed to achieve important strategic goals by identifying how specific R&D activities can relate to integrated technical capabilities needed to achieve strategic objectives. The process of identifying the needed science and technology must be focused by developing a concept of the technological system that would enable achievement of that goal. This task is particularly difficult in the case of carbon capture and sequestration because there has been, heretofore, no paradigm for such a system (Victor 1998).

Our road map gives a top-level picture of a carbon capture and sequestration system and its linkages to the energy system. We have concentrated principally on the development of scientific understanding that is needed for specific capture and sequestration functions, including specific changes in components of the existing energy system that would simplify and/or lower the cost of capture and disposal. Many capture and sequestration technologies are discussed in detail in Chaps. 2–7. Each can be developed and improved individually. However, the economic cost and effectiveness of the overall carbon capture and sequestration system depend on the effective combination of many scientific advances. Their relative importance must finally be judged in the context of the integrated technology system.

After identifying the technology goals and the integrated technology system needed to satisfy those goals, our next step was to assess the alternative technological pathways that might lead to an integrated carbon sequestration technology system. The approach was to construct these pathways within a technological hierarchy. The highest level of the hierarchy is the integrated technology system—in this case, the carbon capture and sequestration system. The hierarchy base is supported by the science and technology capabilities that are needed to develop the technologies that make the system economical and effective.

1.4.1 Foundations for an Expanded National Program in Carbon Sequestration

Sequestration studies began in 1977 (see End Note 1), but an upsurge of interest in them has occurred only recently. In the past two years, several key government studies of carbon management and energy have highlighted carbon sequestration as an approach with high potential where much R&D is needed.

For example, the potential importance of carbon sequestration has been underscored by the President's Committee of Advisors on Science and Technology report titled *Federal Energy Research and Development Agenda for the Challenges of the 21st Century* (PCAST 1997). Specifically, the report recommends that a much larger science-based CO_2 sequestration program be developed with the budget increasing from the current $1 million per year to the vicinity of tens of millions. The report further states that the R&D should be performed in a collaborative way between DOE's offices of Fossil Energy and Energy

Research (now Office of Science) and the U.S. Geological Survey. International collaboration is also strongly encouraged.

Although the current DOE carbon sequestration program is modest in scale, many of the foundations have already been built for significantly expanding this effort. The DOE Office of Science program on CO_2 sequestration includes both the Office of Basic Energy Sciences (BES) and the Office of Biological and Environmental Research (BER). The primary relevant goal for BES is to develop major new fundamental knowledge that crosscuts DOE's applied programs related to carbon management, including such disciplines as materials sciences, chemical sciences, geosciences, plant and microbial biosciences, and engineering sciences. BES has longstanding programs in fundamental research, such as improved materials synthesis and combustion engineering for more efficient energy technologies, improved catalysts for low-carbon industrial processes, improved understanding of biological mechanisms of carbon fixation, and improved understanding of fluid flow in the subsurface for geological sequestration (www.er.doe.gov/production/bes/bes.html).

In 1999, a new program in BES and BER will be initiated to conduct research in carbon management, including carbon sequestration, as a result of the climate change technology initiative. The subjects will include sequencing genomes of methane- and hydrogen-producing microorganisms; enhancing the natural terrestrial and oceanic fluxes of CO_2; and improving the understanding of biological carbon fixation, materials, catalysts, combustion chemistry, and physics and chemistry of geological reservoirs.

BER has a longstanding fundamental research program on the global carbon cycle. Current research focuses on atmospheric measurements of carbon fluxes and related processes, terrestrial carbon fluxes, and advanced biological investigations of carbon in terrestrial and ocean margin systems. A key element of terrestrial carbon research involves Ameriflux, which is a network of CO_2 flux measurements across North, Central, and South America to quantify net CO_2 exchange between the atmosphere and representative terrestrial ecosystems. Free Air CO_2 Enrichment (FACE) experiments provide information about changes in the carbon content of ecosystems under increased concentrations of atmospheric CO_2, altered temperatures, and altered precipitation regimes. Relevant information can be found at http://www.er.doe.gov/production/ober/gc/accc-fr.html and http://cdiac.esd.ornl.gov/programs/ameriflux. Ocean research focuses on molecular biological approaches to understanding the coupling between carbon and nitrogen cycles (http://www.er.doe.gov/production/ober/gc/accc-fr.html). BER also sponsors a program, Integrated Assessment of Global Climate Change, that supports research in understanding carbon management frameworks for integrated assessment modeling activities.

DOE's Office of Fossil Energy has a program on CO_2 capture and sequestration to develop and demonstrate technically, economically, and ecologically sound methods to capture, reuse, and dispose of CO_2. In 1998, DOE made awards for 12 "cutting-edge" research projects, ranging from the use of CO_2-absorbing algae growing on artificial reefs to deep-ocean or deep-saline-reservoir greenhouse gas disposal. Some of these projects may be selected for further development. (Details on this solicitation can be found at www.fe.doe.gov).

The Office of Fossil Energy has recently undertaken an initiative to provide formal management direction to sequestration program activities and to establish program content and funding priorities. A team has been assembled to define a research strategy clearly and to ensure coordination with internal and external stakeholders. In making its recommendations, the team will draw heavily from this report. In FY 1999, the second phase of the Fossil Energy novel concept investigations will obtain the required engineering and economic data to proceed to proof-of-concept. In the areas of geological and ocean sequestration, international government/industry projects will continue.

In 1991 the International Energy Agency (IEA) established a Greenhouse Gas R&D Programme focused on analyzing technologies for capturing, using, and storing CO_2. It has expanded to include methane, as well as forestation options. The program is currently in its third 3-year phase and has support from 16 countries (including the United States) and a growing number of industrial organizations. (Details on this program can be found at www.ieagreen.org.uk.)

In addition to government studies, industry is moving ahead with development of CO_2 sequestration technologies:

- The World Resources Institute formed a consortium with General Motors, Monsanto, and British Petroleum to address the fundamental issues of global energy supply, climate change, and economic growth—paths to stabilizing CO_2 concentrations at levels reducing risks of climate change (WRI 1998).
- Since October 1996, Statoil, a Norwegian energy company, has been separating CO_2 from natural gas and injecting it, at a rate of 1 million tonnes per year, into a deep saline reservoir 800–1000 meters below the ocean floor in the North Sea (see Chap. 5).
- About 70 oil fields use CO_2 injection to recover additional crude oil.
- Various oil companies have proposed to sequester CO_2 at the rate of 30 million tonnes of carbon per year in the deep aquifers adjacent to the Natuna gas field, in the South China Sea, when that field comes into production.
- Many domestic and international forest preservation and management projects sequester carbon by reducing deforestation and harvest impacts. Forest management can also enhance existing carbon sinks.

These industrial efforts are very important, but the amounts of CO_2 sequestered are very small compared with overall emissions. Considerable R&D investment by government and industry is needed to enable sequestration of sufficient quantities of CO_2 to mitigate any adverse effects resulting from CO_2 emissions.

1.4.2 The Need for a National R&D Plan for Carbon Sequestration

Carbon sequestration is promising as a carbon management strategy, but its potential cannot be evaluated and realized without a broad program of research, development, and demonstration. The specific components of such a plan are the subjects of Chaps. 2–7. The framework for an integrated carbon sequestration system is presented in Chap. 8.

There are many ways to move ahead on sequestration. Some technologies are already sufficiently developed to be tested in field research experiments (e.g., injecting CO_2 into a geological formation and monitoring its form, location, and stability). As technologies progress, their implications for global climate change policy should be evaluated (Parson and Keith 1998).

Many sequestration technologies and practices will require further fundamental scientific and engineering studies before field testing. For example, there are known agricultural practices for increasing storage of carbon in plant roots and soil, but much research needs to be done to design effective methods for enhancing carbon storage in ecosystems and determine their impacts.

1.5 END NOTES

1. Avoidance of CO_2 emissions through physical capture of CO_2 from power plants and disposal of CO_2 in the deep ocean was first proposed by Marchetti (1977). In the United States, preliminary studies were conducted at Brookhaven National Laboratory (Steinberg 1984).

   However, it was not until 1990 that planning research efforts were undertaken in this field. Since then, many conferences and studies have been conducted on options for the capture and disposal or reuse of CO_2 from large stationary sources. Much of this work has been done under the auspices of IEA's Greenhouse Gas R&D Programme and the successful conference series on CO_2 removal and disposal. It should also be noted that the Offices of Fossil Energy and Science jointly sponsored a research needs assessment (Herzog 1993) and a white paper (Herzog 1997) on this subject. Both of these reports were completed at the Massachusetts Institute of Technology.

   In the past two years, four important government documents have appeared that highlight the potential for carbon sequestration and the need for further work. There are recent reports by the President's Council of Advisors on Science and Technology; *the Federal Energy R&D Report*; the study by 11 DOE laboratories called *Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions* (National Laboratory Directors 1997); *and Carbon Management: Assessment of Fundamental Research Needs,* a product of a series of DOE workshops (DOE 1997). Important conferences and workshops that have addressed carbon sequestration have been four international conferences on CO_2 removal, the International Conference on Greenhouse Gas Control Technologies in Interlaken, Switzerland in August 1998; the Fuels, Decarbonization, and Carbon Sequestration Workshop (Socolow 1997); the Stakeholders' Workshop on Carbon Sequestration (Herzog 1998); and "Carbon Sequestration in Soils: Science, Monitoring, and Beyond" held December 1998 in St. Michaels, Maryland, and organized by Pacific

Northwest and Oak Ridge National Laboratories. These reports and others indicate that the potential for sequestration is quite high but largely unexamined.

2. Several road-mapping activities under way at DOE are related to the development of this carbon sequestration road map. For example, the Office of Industrial Technologies is carrying out the Industries of the Future program that involves the development and implementation of technology road maps for the most energy-intensive industries, including aluminum, steel, chemicals, glass, and forest products. Among these activities is a joint effort under way with the chemicals, forest products, and agricultural industries to plan for the future of plant/crop-based resources, which includes the development of new bioenergy technologies for the coproduction of fuels, power, and industrial feedstocks.

   There is also a road map under development for power generation technologies by the offices of Fossil Energy, Nuclear Energy, and Energy Efficiency and Renewable Energy in collaboration with the heat and power generation industries. The Electric Power Research Institute is developing technology road maps for electric power generation, transmission, distribution, storage, and end use. These efforts all involve the joint development and deployment by government and industry of advanced technologies, many of which will result in lower carbon emissions, thus affecting the source and amount of man-made carbon emissions to be sequestered in the future.

1.6 REFERENCES

DOE (Department of Energy) 1997. *Carbon Management: Assessment of Fundamental Research Needs*, USDOE/ER-0724, Washington, D.C.

EIA (Energy Information Administration) 1998a. *Annual Energy Review 1997*, DOE/EIA-0384(97), U.S. Department of Energy, Washington, D.C.

EIA (Energy Information Administration) 1998b. *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97), U.S. Department of Energy, Washington, D.C.

Herzog, H. J., E. M. Drake, J. Tester, and R. Rosenthal 1993. *A Research Needs Assessment for the Capture, Utilization, and Disposal of Carbon Dioxide from Fossil Fuel-Fired Power Plants*, DOE/ER-30194, U.S. Department of Energy, Washington, D.C.

Herzog, H., E. Drake, and E. Adams 1997. *CO_2 Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change: A White Paper,* Massachusetts Institute of Technology Energy Laboratory.

Herzog, H. J., ed. 1998. *Proceedings of the Stakeholder's Workshop on Carbon Sequestration*, MIT EL 98-002, Massachusetts Institute of Technology Energy Laboratory, June.

Hoffert, M. I., K. Caldeira, A. K. Jain, E. F. Haites, L. D. D. Harvey, S. D. Potter, M. E. Schlesinger, S. H. Schneider, R. G. Watts, T. M. L. Wigley, and D. J. Wuebbles 1998. "Energy Implications of Future Stabilization of Atmospheric CO_2 Content," *Nature* (395): 881–4.

Houghton, R. A. 1995. "Land-Use Change and the Carbon Cycle," *Global Change Biology* 1: 275–87.

IPCC (Intergovernmental Panel on Climate Change) 1996. *Climate Change 1995: The Science of Climate Change*, J. T. Houghton, L. G. Meira Filho, B. A. Collander, N. Harris, A. Kattenberg, and K. Maskell, eds., Cambridge University Press, Cambridge, UK.

Keeling, C. D., and T. P. Whorf 1998. "Atmospheric CO_2 Records from Sites in the SIO Air Sampling Network," in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.

Marchetti, E. 1977. "On Geoengineering and the CO_2 Problem," *Climate Change* 1(1): 59–68.

Marland, G. H., R. J. Andres, T. A. Boden, C. Johnston, and A. Brenkert 1998. *Global, Regional, and National CO_2 Emission Estimates from Fossil Fuel Burning, Cement Production, and Gas Flaring*: 1751–1995 (rev. January 1998), available at http://cdiac.esd.ornl.gov/ndps/ndp030.html (accessed 1/6/99).

National Laboratory Directors 1997. *Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions*, Oak Ridge National Laboratory.

Parson, E. A., and D. W. Keith 1998. "Fossil Fuels Without CO_2 Emissions," *Science* 282 (Nov. 6).

PCAST (President's Committee of Advisors on Science and Technology) 1997. *Federal Energy Research and Development Agenda for the Challenges of the Twenty-First Century*, U.S. Department of Energy, Washington, D.C., November.

Socolow, R., ed. 1997. *Fuels Decarbonization and Carbon Sequestration: Report of a Workshop*, Report 302, Princeton University/Center for Energy and Environmental Studies, September.

Steinberg, M. 1984. *An Analysis of Concepts for Controlling Atmospheric Carbon Dioxide*, DOE/CH/00016-1, Brookhaven National Laboratory.

Victor, D. C. 1998. "Strategies for Cutting Carbon," *Nature* (395): 837–38.

Wigley, T. M. L., R. Richels, and J. A. Edmonds 1996. "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," *Nature* 379 (January 18): 240–3.

WRI (World Resources Institute) British Petroleum, General Motors, and Monsanto 1998. *Climate Protection Initiative: Building a Safe Climate, Sound Business Future*. Washington, D.C.

1.7 ACKNOWLEDGMENTS

Special appreciation is due to Michael P. Farrell for providing the discussion of the global carbon cycle in Sect. 1.2.1 and to Marilyn A. Brown for translation of the Energy Information Administration (EIA) U.S. energy flow data into carbon equivalents in Fig. 1.3.